Cosmogony and Stellar Evolution.[1]

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II.

The Evolution of Stellar and Planetary Systems.

IN the last lecture we followed up, so far as is permitted by modern theoretical and observational research, the train of ideas on which Laplace had based his nebular hypothesis. Theoretically we found that a shrinking mass of rotating gas ought in time to assume a lenticular shape, after which further shrinkage would result in the ejection of matter from the sharp edge of the lens. It is suggested that the spiral nebulæ form instances of this process, the spiral arms being the ejected matter and the central nucleus the remnant of the original rotating mass of gas. The spiral arms are observed to break up into condensations, a process of which a theoretical explanation can readily be given. But on inserting approximate numerical values it is found that each condensation must have a mass comparable with that of a star. In the spiral nebulæ we are watching, not the birth of planets, which Laplace attempted to explain by his nebular hypothesis, but the birth of the stars themselves. The process is, in its main outlines, identical with that imagined by Laplace, but is on a more stupendous scale.

The separate stars when set free from the parent nebula are themselves shrinking and rotating masses of gas; they may be thought of as small-scale models of the nebula which gave them birth. We naturally inquire whether the process of evolution of these small-scale models will be the same as in the parent nebulæ. The answer is provided by a mere inspection of the physical dimensions of the formulæ which govern the dynamical processes of evolution. It is found that, as regards the central mass of lenticular shape, the small-scale model operates precisely like the bigger mass. Any rotating mass of gas, provided only that it is sufficiently great to hold together under its own gravitation, will in due course assume the lenticular shape and discharge matter from its equator. But as regards the ejected matter, the small-scale model does not work in the same way as the bigger mass. If the matter ejected from a big mass forms a million condensations, the matter yielded from a small mass of one-millionth part of the size will not form a million tiny condensations—it will form only one condensation, and will, moreover, form this one only if other physical conditions are favourable. In actual fact, when regard is had to numerical values, it is found that other physical conditions are not favourable. The matter will be ejected at so slow a rate that each small parcel of gas will simply dissipate into space without any gravitational cohesion at all. Some molecules will probably escape altogether from the gravitational field of the central star, while the remainder will form merely a scattered atmosphere surrounding the star. For this reason, in addition to others, the conception of Laplace does not appear to be capable of providing an explanation of the genesis of planetary systems.

So far we have studied the way in which a mass of gas would break up under increasing rotation. As a matter of theoretical research it is found that a mass of homogeneous incompressible substance, such as water, would break up in an entirely different fashion. It is further found that there are only these two distinctive ways in which a break-up can occur, so that if a mass the rotation of which is continually increasing does not break up in one way it must break up in the other. As a star, from being a mass of gas of very low density, shrinks into a liquid or plastic mass of density perhaps comparable with that of iron, it passes through a critical point at which there is a sudden swing over from one type of break-up to the other. This critical point occurs when the density of the star has become such that the ordinary gas-laws are substantially departed from throughout the greater part of the star's interior. This density is, however, precisely that which marks the demarcation between giant and dwarf stars. Thus the general conclusion of abstract theory is that a giant star will break up under increasing rotation in the way we have already had under consideration, but that a dwarf star will break up in the same way as a homogeneous incompressible mass, such as a mass of water.

The discovery of the method of break-up in this second case forms one of the most difficult problems of applied mathematics. In spite of the labours of many eminent mathematicians, among whom may be mentioned Maclaurin, Jacobi, Kelvin, Poincaré, and G. H. Darwin, the problem is still far from complete solution. It is found that as the rotation of a homogeneous mass increases the boundary remains of exact spheroidal shape until an eccentricity of 0·8127 is reached, at which the axes are in the ratio of about 12 : 12 : 7. With a further increase of rotation the boundary ceases to be a figure of revolution; it becomes ellipsoidal and retains an exact ellipsoidal shape until the axes are in a ratio of about 23 : 10 : 8. Beyond this it is impossible for the mass to rotate in relative equilibrium at all, and dynamical motion of some kind must ensue. At first a furrow forms round the ellipsoid in a cross-section perpendicular to the longest axis, but the cross-section in which the furrow appears does not divide the figure symmetrically into equal halves. The furrow deepens, and at this stage the problem eludes exact mathematical treatment. It appears highly probable, although it cannot be rigorously proved, that the furrow will continue to deepen until it separates the figure into two unequal masses. On the assumption that this is what would actually happen we may conjecture that the process we have been describing is that of the fission of a single star into a binary of the familiar type, but the conjecture is beset by many difficulties. To mention one only: if we have truly described the history of a star before fission, the star ought during a moderate part of its life to possess an ellipsoidal figure, and as this rotated the light received from the star ought to vary to an extent which just before fission might amount to 0·9 magnitude. Yet I believe there are only three known stars whose variation of light is such as could possibly be accounted for by an ellipsoidal surface, and even in these cases the interpretation is doubtful. On the other hand, very considerable reassurance is provided by the researches of Russell on multiple stars. After a star has broken into two parts by fission both parts will continue to shrink, so that either or both may in turn again break up, and a triple or quadruple system be formed. Russell finds that in a multiple system which has been formed in this way the distance between the stars formed by subsequent fissions cannot be more than a small fraction, at most about one-fifth, of the distance between the pair generated by the original fission. A mere glance at a catalogue of multiple stars will show that this condition is fulfilled by the majority of observed systems. On account of foreshortening the apparent separations will not always appear to conform to the rule, but Russell has shown, as the result of a careful statistical discussion, that the exceptions agree, both in kind and in number, with what might be expected from foreshortening.

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[1] Lectures delivered at King's College on May 17 and 24. Continued from p. 560.

We have now traced out the life-history of a rotating and shrinking mass from beginning to end, from its start as a gaseous mass of very low density, through its assumption of a lenticular shape and its first break-up as a spiral nebula, through its subsequent condensation into separate stars, to their final fissions into binary and multiple systems. The picture has been distressingly incomplete, and it cannot be denied that the story is beset by many difficulties and uncertainties. The mathematical investigation is far from perfect; gaps in theory have frequently been bridged by nothing more substantial than conjecture; in many cases there has been room for grave doubt as to the identification of observed formations with those predicted by theory; in one instance at least a formation predicted by theory, the ellipsoidal star, is practically unknown to the observing astronomer. But, after allowing for all imperfections, we have a tolerably complete knowledge, so far as the main outlines are concerned, of the whole chain of configurations which will be assumed in turn by the rotating shrinking mass of Laplace, and on this chain there does not appear to be any room for the solar system.

Apart from this, there are weighty reasons for thinking that our system has not been formed as the result of a rotational break-up. The angular momentum of a system remains constant during a process of breaking up, and, as was pointed out by Babinet in 1861, even if the whole angular momentum of the solar system were now concentrated in the sun it would still have less than a quarter of the angular momentum requisite for breaking up at its present density. Except in the improbable event of the solar system, since fission, having been robbed by a passing star of by far the greater part of its angular momentum, its rotation can never have been sufficient to cause a break-up. Clearly there is a case for examining whether some other agency cannot produce a system such as ours.

The sun and moon, as we know, raise tides on our earth the height of which forms only an inappreciable fraction of the earth's radius. If our earth were replaced by a mass of liquid or gas of low density the fraction would be greater, varying inversely as the density of the mass. If the sun and earth were placed much nearer to one another than now the tides would be increased in the ratio of the inverse cube of their distance apart. We can easily imagine conditions under which the heights of the tides would be comparable with the radius of the earth, and here the simple formulæ which the mathematician uses to calculate the heights of terrestrial tides become useless. The general investigation of the succession of shapes which will be assumed by a gaseous or plastic mass as the tidal forces on it continually increase presents a difficult but not altogether intractable problem for the mathematician.

It is found that the tides will be of the general type with which we are familiar on the earth until a certain critical height of tide is reached. This critical height is comparable with half the radius of the mass, being greater or smaller according as the mass is of more or less uniform density. After this critical height has been passed, there is no longer a configuration of equilibrium under the tidal forces. Dynamical motion ensues, and the general nature of this motion will consist in the ejection of two arms or jets of matter, one towards the attracting mass and one, which may be smaller, or may be absent altogether, in the exactly opposite direction. If the tide-generating forces should be suddenly removed at this stage the jets would, of course, fall back into the mass from which they emerged, and this would in time resume its spherical form. But if the tidal forces persist, the jets will continue to be thrown out, and it can be shown that a continuous distribution of density in these jets would be unstable, just in the same way, and for similar reasons, as in the case we previously discussed of the jets thrown out from a rotating mass of gas. Condensations would form in the jets, and ultimately the jet would break up into separate detached masses.

According to the tidal hypothesis of the origin of the solar system, the sun was at some past time subjected to intense tidal forces from a passing star, the sequence of processes we have just described took place, and the emitted jet broke into fragments which are our present system of planets. From the mathematical investigation on which this hypothesis is based, it appears that the fragments would each be comparable in mass with the original sun if the matter of the sun had been of approximately uniform density, but would be very small by comparison if the sun had been gaseous with high central condensation. The smallness of the masses of the planets in comparison with that of the sun must, therefore, be taken as indicating that the sun was in a gaseous state with high central condensation when the planets were born. The jets of matter thrown out would also be gaseous, but would rapidly cool in the process of ejection, and might soon liquefy or even solidify. It can be shown that the planets which would be formed out of the middle portion of such a jet ought to be much more massive than those formed near the ends, and this may possibly provide an explanation of the comparatively great masses of Jupiter and Saturn. We imagine that the planets at first described orbits under the combined gravitational action of the sun and the passing star by which the cataclysm was caused, but as this star receded they were left revolving, as at present, around the sun. During their earlier motion they may themselves have been broken up by the tidal action of one or both of the big masses present, and such a process may explain the origin of the satellites of the planets.

Such, in its main outlines, is the tidal theory of the genesis of the solar system. So far as can be seen, a vast amount of further mathematical research is needed before it can be either definitely accepted or finally condemned. For myself, I find it more acceptable than the rotational theory, or any other hypothesis so far offered, of the origin of the solar system. Time does not permit of a discussion of its difficulties, but I may perhaps conclude by stating what seem to me to be its main advantages over the rotational theory.

(i) It escapes the well-known criticism of the rotational theory that the present angular momentum of the solar system is too small to be compatible with a previous rotational break-up, and I do not know of any similar quantitative criticism which can be brought against the tidal theory.

(ii) The solar system is arranged with reference to two planes—the invariable plane of the system, which contains the orbits of the outer planets, and a second plane inclined at about 6° to the former plane, which contains the sun's equator and the orbit of Mercury. A system which had broken up by rotation alone ought to be arranged symmetrically about one plane—the original invariable plane of the system. On the tidal theory the two planes of the solar system are readily explained as being the plane in which the tide-raising star moved past the sun, and the original plane of the sun's rotation.

(iii) Theoretical investigations suggest that there is only one possible end for a rotating system, namely, a binary or multiple star of the type familiar to astronomers, and it is quite certain our system is not of this type. Similar investigations on tidal action suggest that the final end of a system broken up by a tidal cataclysm ought to show many of the features of our present solar system.

The Edinburgh Meeting of the British Association.

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LOCAL ARRANGEMENTS.

THE British Association meeting to be held during the week September 7–14 is the fifth meeting of the Association to be held in Edinburgh, the previous meetings having been in 1834, 1850, 1871, and 1892. The last of these, under the presidency of a distinguished son of Edinburgh—Sir Archibald Geikie—was a memorable and successful meeting, and the citizens of Edinburgh are anxious to make the forthcoming meeting no less notable and successful.

As at the last Edinburgh meeting, the reception room, the headquarters of the Association, and the bureau of information will, by permission of H.M. Office of Works, be the Parliament Hall, in which the Scottish Parliament met until the Treaty of Union in 1707. One of the courts adjacent to the hall will be used for the meetings of council and of other administrative committees, and by permission of the Faculty of Advocates rooms in the advocates' library, which is adjacent to Parliament Hall, have been provided for the use of the president and general officers, and the advocates' writing-room has been placed at the disposal of members. The attention of members is directed to the rule prohibiting smoking in any part of the library and in Parliament Hall; a smoking-room is provided near the reception room. The usual postal (including telegraphic) facilities will be provided in the post office at the entrance to the reception room.

The sectional meetings will be held in the lecture rooms of the University. Six of the sections will meet in the Old College, two in the adjacent departments of natural philosophy and engineering, three sections and the conference of delegates in the University New Buildings (the medical school of the University), and the remaining two in the department of agriculture and forestry, which is within four minutes' walk of the University New Buildings and of the Old College. In connection with several of the sectional meetings, laboratory accommodation will be available for apparatus and specimens which members may desire to exhibit to illustrate their communications to the sections.

Writing-rooms will be provided in the University and in the Unions. The University library in the Old College is to be open so that members may consult books and the principal literary and